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Wafer level fabrication of vibrational energy harvesters using bulk PZT sheets

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Abstract

This paper presents a complete wafer level microfabrication process for the production of unimorph MEMS energy harvesters based on bulk PZT. Recently, piezoelectric harvesters designed to take advantage of the high quality piezoelectric properties of bulk PZT have been fabricated using local placement and bonding of individual PZT pieces and large proof masses at the chip level. With the process presented here, 16 piezoelectric energy harvesters have been fabricated in parallel at the wafer level by bonding a single bulk PZT sheet to a silicon wafer and processing the wafer with standard microfabrication techniques including an electrodeposition step to deposit a thick ($> 200 \mu\text{m}$) nickel proof mass. The fabricated harvesters are able to generate an output power of $116 \mu\text{W}$ at an acceleration of 1 g and a resonant frequency of 203 Hz .

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Keywords: Wafer level fabrication; vibration energy harvesting; bulk PZT sheets; bonding

1. Introduction

At present, several approaches are being developed to realize a battery-independent energy source for powering low power consumption devices such as wireless sensor networks, medical implants, and environmental monitoring systems. Harvesting kinetic energy presented in the form of mechanical vibrations has garnered interest recently due to the ubiquitous presence of environmental motion that can

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be easily transformed into useful electrical power through several methods of electromechanical transduction. Piezoelectric materials have received the most attention due to the ease of direct conversion from vibrational energy into electrical energy achieving high power densities and straight-forward integration [1]. Several piezoelectric materials exist; however, the materials of interest for application in MEMS devices are mainly restricted to PZT (lead zirconate titanate), ZnO (zinc oxide), and AlN (aluminum nitride). Of these, bulk PZT is readily available and offers a high piezoelectric coefficient and high electromechanical coupling when compared to deposited films and screen printed PZT [3-4]. Compared to the latter, PZT sheets do not require high temperature firing, the deposition of stable electrodes or piezoelectric poling after deposition. Thus, here we propose a wafer level fabrication process that avoids the placement of PZT pieces and proof masses on each individual chip while still benefiting from the properties of bulk PZT. This is achieved by transferring a PZT sheet onto a silicon wafer on which a nickel mass can be grown using an electrodeposition process at the wafer level.

2. Design and fabrication

Piezoelectric harvesters consist typically of one or several piezoelectric layers supported by an elastic cantilever beam from which a mass is suspended. The design of the piezoelectric harvester in this work is based on a unimorph cantilever with a proof mass at the free end as illustrated in Fig. 1.

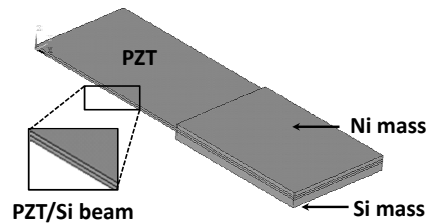


Figure 1. Schematic structure of a piezoelectric harvester (Bulk PZT on silicon beam with silicon and nickel proof masses).

The supporting elastic layer and a portion of the proof mass are made by silicon. A bulk PZT sheet (130 μm) is used as a piezoelectric layer which is positioned on top of the Si support layer and is operated in transverse (d_{31}) mode. An additional proof mass, an electrodeposited layer of nickel, is added to the end of the beam and positioned above the silicon mass in order to tune the resonant frequency to the range of interest. The thickness ratio between the unimorph layers ($t_{\text{PZT}}/t_{\text{Si}}$) is one of the key parameters that must be taken into account in the design. As demonstrated in [4], the thickness ratio of these layers should be close to 1 in order to optimize the output power generated from the harvester.

Table 1. Bulk PZT harvester design parameters

Sample	Piezoelectric volume (mm^3)	Beam volume (mm^3)	Mass (Si) volume (mm^3)	Mass (Ni) volume (mm^3)
A	$7.5 \times 15 \times 0.13$	$7.5 \times 15 \times 0.13$	$7.5 \times 7.5 \times 0.525$	$7.5 \times 7.5 \times 0.3$
B	$7.5 \times 22 \times 0.13$	$7.5 \times 22 \times 0.13$	$7.5 \times 10 \times 0.525$	$7.5 \times 10 \times 0.3$

To determine the piezoelectric beam dimensions and their resonant frequencies, a multi-physics FEA simulation tool was applied. In this work, the resonant frequency of the harvesters was simulated in ANSYS. In order to harvest energy from periodic vibrations at moderate frequencies (50-400 Hz), the bulk PZT harvesters were designed with the dimensions presented in Table. 1.

The proposed wafer level fabrication process for unimorph energy harvesters using a bulk PZT sheet is illustrated in Fig 2(a). The process begins with a 525 μm -thick silicon substrate. Through-holes (130 μm deep) used to access the electrical contact on the bottom electrode of the PZT are first patterned by DRIE (a). These holes are also used to define the thickness of the silicon beam. A 200 nm-thick LPCVD silicon nitride film is then deposited on both sides to provide electrical isolation as well as a masking layer for anisotropic wet etching of silicon. Backside openings in the silicon nitride are defined using UV lithography followed by RIE etching (b). The exposed areas of the silicon are etched in a KOH solution to define the cantilever and the silicon portion of the proof mass (c). A bulk PZT sheet (130 μm) is then bonded to the frontside of the silicon wafer using a UV activated glue (DELO 4552) (d). To further decrease the resonant frequency of the cantilever, a 300 μm Ni mass is electrodeposited directly on the top side of the PZT layer providing an additional proof mass to the tip of cantilever (e). The wafer is then diced into individual cantilevers and mounted onto a PCB for characterization (Fig. 2(b)).

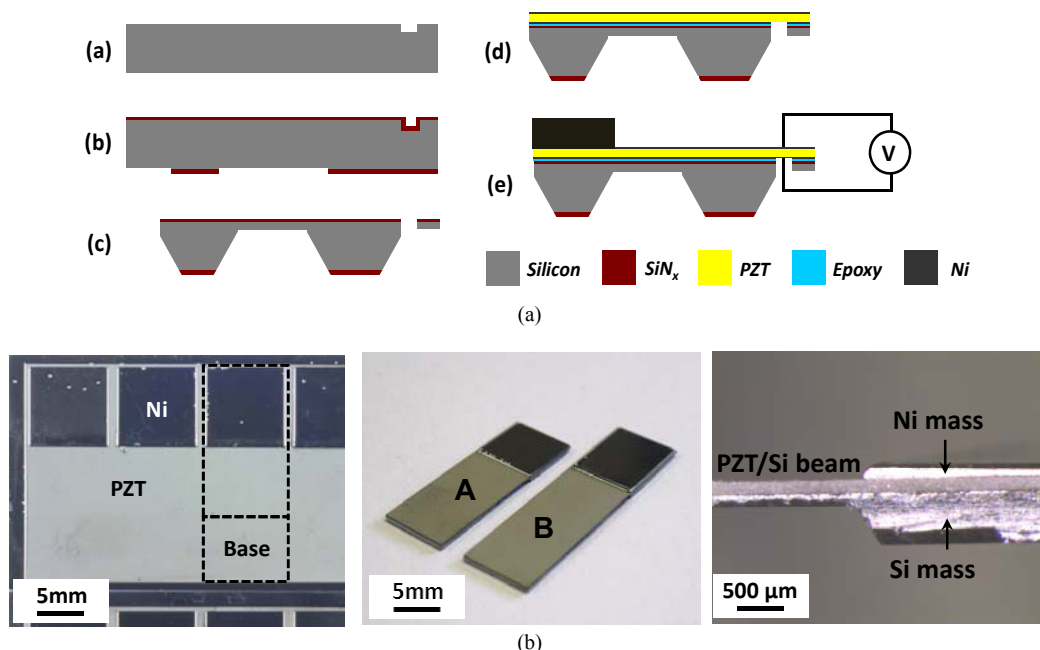


Figure 2. (a) Schematic of the fabrication process for the bulk PZT harvesters; (b) optical images of the bulk PZT/Si wafer after Ni electrodeposition. The cantilever structure is separated by dicing.

3. Results and discussion

Once mounted, the performance of the bulk PZT harvesters was investigated using an electrodynamic shaker and evaluated as a function of frequency, acceleration and resistive load. The resonant frequencies of the devices, type A and B, are found at 369 ± 4 and 203 ± 2 Hz respectively which correspond well with simulations. The measured power depends on the resistive load (Fig. 3). The electromechanical coupling coefficient (k^2) of each device was experimentally determined from the frequency shift measured between the open circuit and short circuit configuration (Fig. 3(b)) as discussed in [5]. The data presented in Table 2 shows that the output power from the harvesters is proportional to k^2 . One must keep in mind that the value of k^2 is not only determined by the material constant of the piezoelectric layer; it is also affected by the geometry of the structure, and in particular the volume fraction of the piezoelectric material in the total elastic body [2].

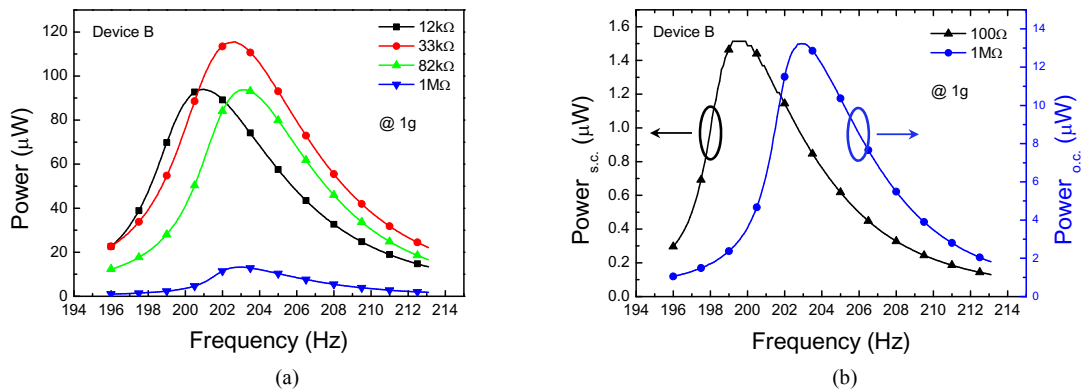


Figure 3. (a) Power output as a function of frequency for various load resistance; (b) The frequencies shift between open circuit and short circuit condition used for calculating k^2 .

With device type B, an average output power of 2.3 μW was obtained under 0.1g. At 1g, the generated power increased to 115.5 μW at an optimal load of 33k Ω .

Table 2. Characteristics and experimental values of the bulk PZT harvesters with 2 different design

Sample	Frequency (Hz)	Input vibration (g)	Power output (μW)	Optimal load (Ω)	Power density ($\text{mW/g}^2/\text{cm}^3$)	k^2 (%)
A	364	1	109.4	22k	1.45	3
B	203	1	115.5	33k	1.10	3.4

4. Conclusion

Vibrational energy harvesters using bulk PZT sheets have been successfully fabricated at the wafer level eliminating the need for individual placement of PZT pieces and proof masses on each harvester while still benefitting from the advantageous properties of bulk PZT. We are currently optimizing the process to thin the PZT layer at the wafer level in order to further improve device performances.

Acknowledgements

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